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A General Purpose Laboratory for Evaluating Livestock Ventilation Systems

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Abstract. *A facility developed at Iowa State University was designed to test and provide research for full-scale livestock housing ventilation systems. A test chamber representing a 24-ft (7.3 m) section of a 42-ft-wide (12.8 m) swine finishing or nursery barn can be outfitted with a complete ventilation system. Operating characteristics of the ventilation system are monitored. These characteristics include ventilation rate, airspeed, and temperature in the animal-occupied zone, air jet profiles generated by the inlets, energy consumption of the ventilation system, and response characteristics of the control system. The chamber contains no animals. Sensible heat production is simulated with cone resistance heaters. Equipment in production barns such as feeders, waterers, gates, and flooring are included. The test chamber is also equipped with a pit area for conducting pit-ventilation studies. The test chamber, housed within the Air Dispersion Laboratory, is currently in use to investigate pit-ventilation effectiveness, heater control logic, ventilation system performance from manufactured systems, and to verify current recommendations of ventilation performance standards for livestock ventilation systems (Proposed ASAE Standard X567).*

Keywords. *Animal housing, Ventilation, Testing, Laboratory, Air jets, Ventilation efficiency, Ventilation effectiveness.*

State-of-the-art swine facilities utilize complete heating and ventilation systems. Mechanically ventilated buildings can include air inlets, air distribution equipment, exhaust or supply fans, heating and cooling equipment, automatic controllers, and monitors. These components are available from a variety of manufacturers. Often these components are sold as complete systems from a single manufacturer. Other times the components are assembled by a farmer, contractor or consulting engineer from independent sources, and mixed from several companies.

While it is possible to obtain performance information for nearly all components of a ventilation system, it is difficult to determine how the components will interact once they have been installed. For example, independent tests of fans and inlets do not guarantee these components will function as predicted upon installation in a barn. Evaluating all components as a complete system allows for direct observation of air speed and temperature distribution, system energy efficiency, and controller performance.

The purpose of the Air Dispersion Laboratory (ADL) is to study, in the absence of livestock, performance of livestock ventilation systems, and to study in a near-production setting the characteristics of ventilation system components and designs. The following summarizes several ADL features and capabilities and serves as an introduction to the ADL.

Purpose

The purpose of the ADL is to provide a facility for manufacturers and researchers to test fans, inlets, controllers, and auxiliary components simultaneously under controlled laboratory conditions. The ADL was specifically designed to test ventilation *system* performance, not just individual components such as fans, inlets, and controllers. The ADL is equipped to test the following parameters of a complete ventilation system: fresh-air distribution; airflow patterns; Animal Occupied Zone (AOZ) temperature uniformity; AOZ airspeed levels; set-point temperature variability within the AOZ; ventilation rate as a function of static pressure difference; and energy consumption per system CFM airflow

ADL Components

The ADL consists of a post-frame outer shell with the actual test chamber positioned centrally inside. Several features make the ADL unique and many of these are described below.

Structural Features

The actual test chamber is enclosed within a post-frame building 40 ft (12.2 m) wide × 64 ft (19.5 m) long with a 14 ft (4.3 m) eave height (fig. 1). The outer post-frame building eliminates wind effects on fans and provides for artificial ambient conditions during testing. The post-frame outer structure has an overhead door for easy equipment transfer to the facility, three side wall block-outs for

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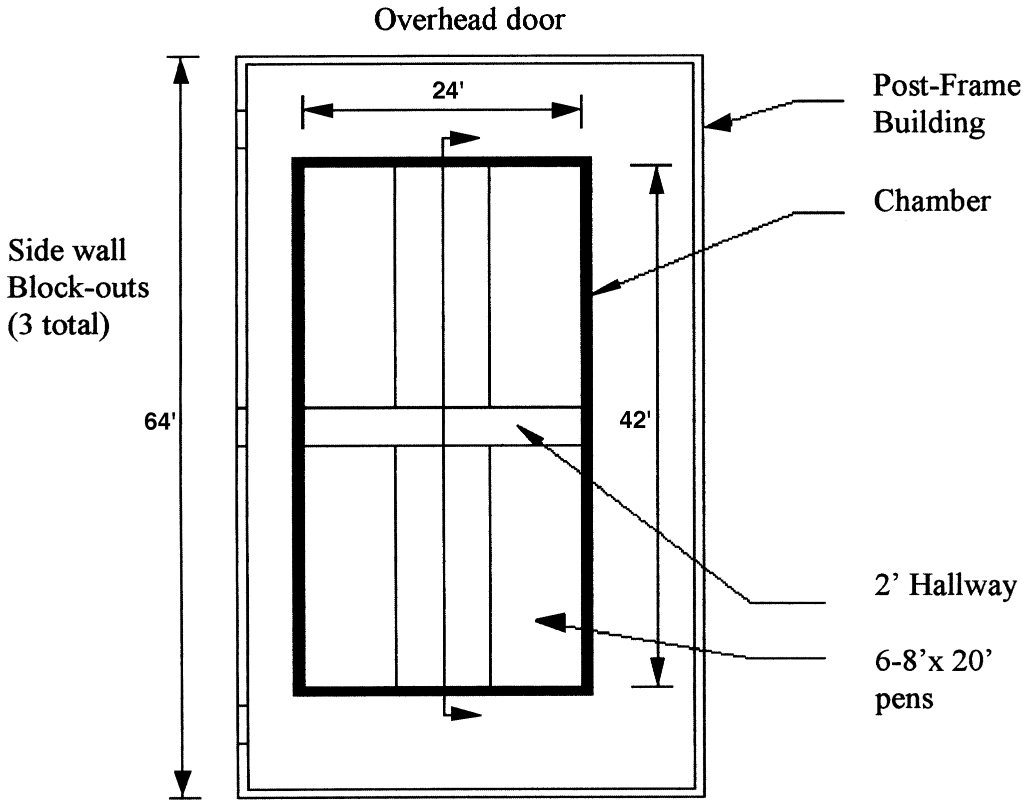


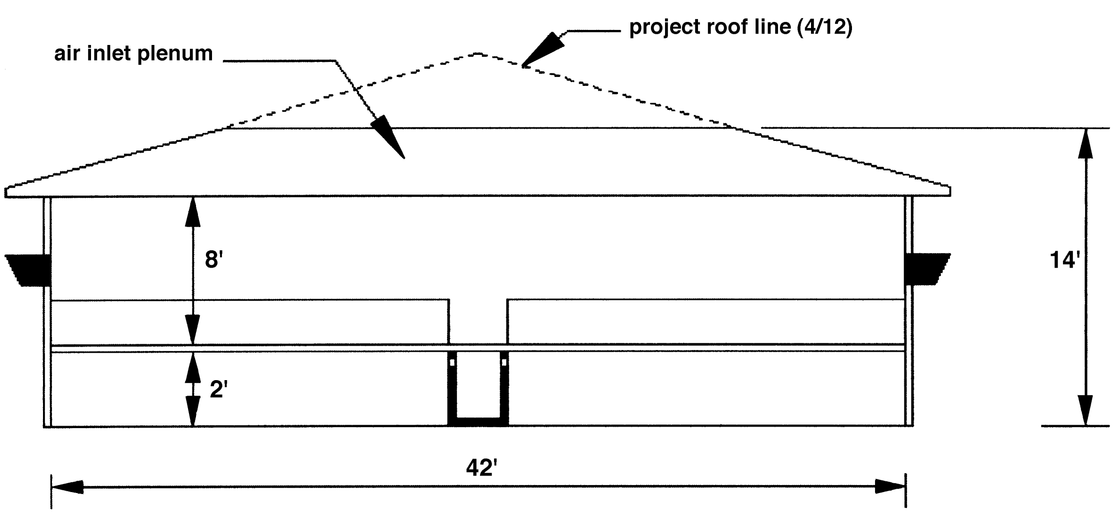


Figure 1–Plan view showing test chamber nestled within the outer post-frame structure and a general cross-sectional view of the actual test chamber (metric equivalents given in text).

allowing outside air to enter the space surrounding the test chamber, and two supplemental heaters for artificially controlling the temperature for the ambient space surrounding the test chamber.

The test chamber is 42 ft (12.8 m) long, 24 ft (7.3 m) wide, and 8 ft (2.4 m) tall. A 2 ft (0.6 m) pit area exists below the chamber flooring, and a 4 ft (1.2 m) attic space exists above the flat ceiling to give the test chamber an overall height of 14 ft (4.3 m). The test chamber can be modeled as a 24 ft (7.3 m) slice of a 42 ft (12.8 m) wide swine finishing house or as a 24 ft wide × 42 ft long full-scale swine nursery. Currently, the test chamber has three 8 ft (2.4 m) wide × 20 ft (6.1 m) long pens on each side of a 2 ft (0.6 m) walkway for a total of six pens. Figure 1 shows a layout of the ADL facility, and figure 2 highlights the dimensions and current features of the test chamber. As shown in figure 2, the test chamber was configured as a wean or nursery-to-finish facility.

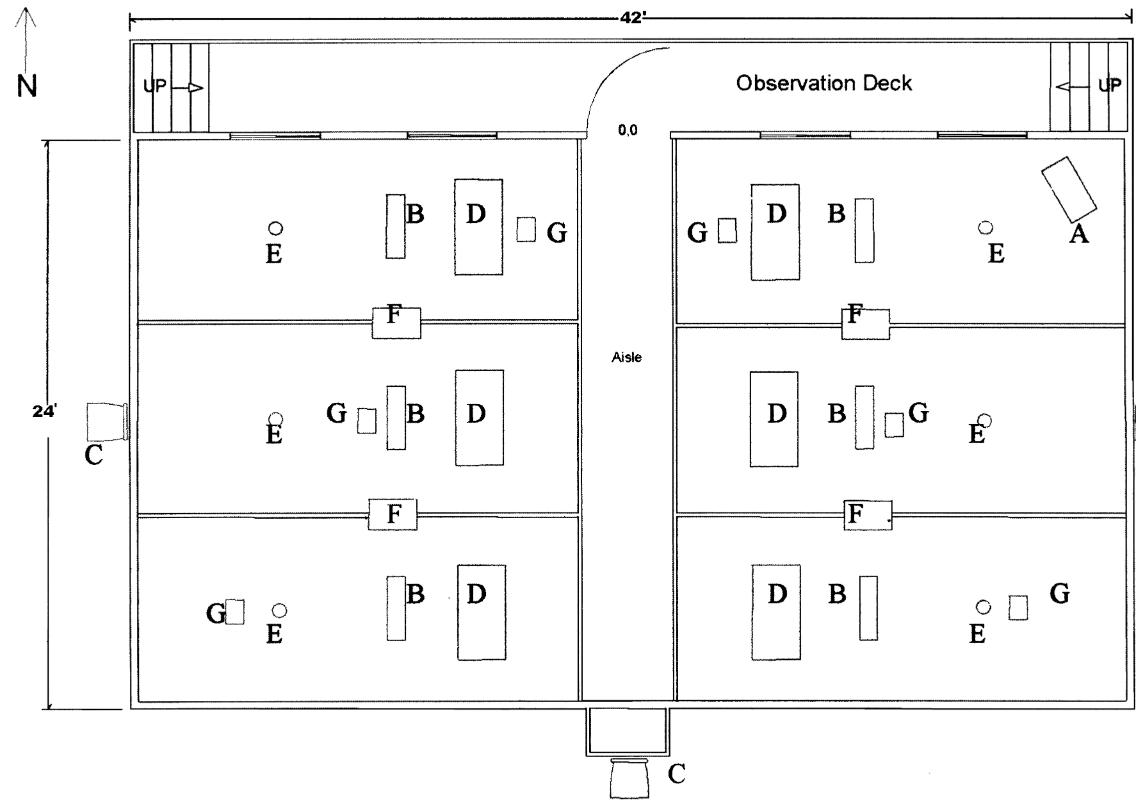


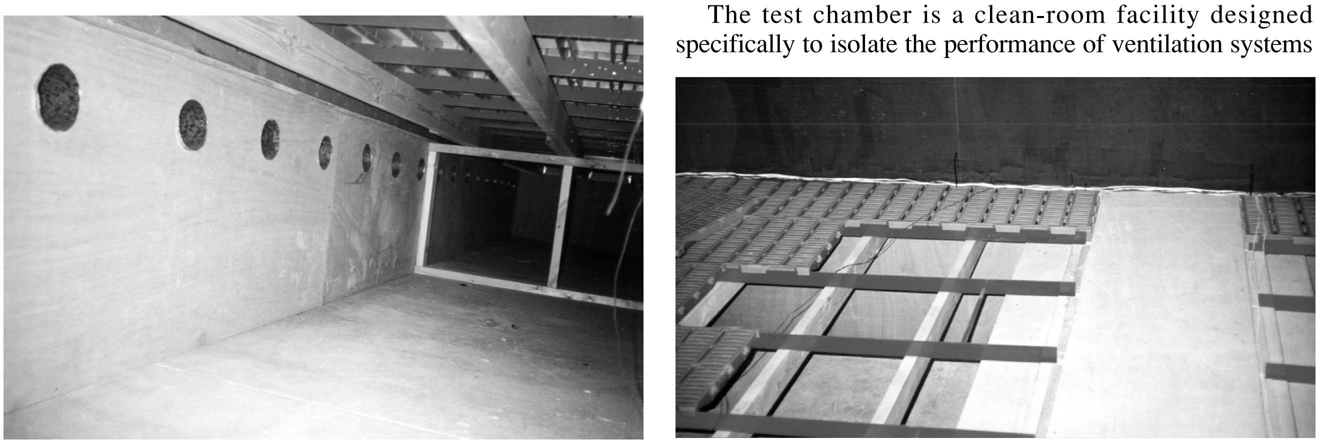
Figure 2–Floor plan of test chamber showing a typical layout of a ventilation system during test. A: LP heater (typical); B: Ceiling inlets (not typical); C: Wall fans (not typical); D: Pig heat simulators (typical); E: Hanging nipple drinkers (typical); F: Feeders (typical); G: Air speed and temperature sensors (typical).

Test Chamber Auxiliary Components

The test chamber is equipped in the same manner as a typical swine wean, nursery or finishing house. The test chamber flooring consists of modular polymer flooring suspended over a 2-ft pit area (figs. 3 and 4). The 2 ft region below the flooring is used to simulate a 2-ft headspace region for conducting pit-ventilation studies. The molded flooring used gives a floor opening that far exceeds concrete slat flooring typically used in finishing facilities. This decision was made so that flexibility in the percent floor opening could be easily adjusted during pit-ventilation studies.

Standard welded steel gates currently separate the test chamber into six 8 ft × 20 ft pens (see fig. 2). Four wet/dry combination feeders and six swinging nipple drinkers complete a basic set of standard components to the test chamber. Feed and water delivery lines were not added to allow more flexibility to the test chamber. Supplemental heat required during cold weather minimum ventilation studies is supplied with an unvented liquid propane unit heater with a manually adjusted heater output between 50 000 and 100 000 Btu/h (14.7 and 29.4 kW).

The test chamber is a clean-room facility designed specifically to isolate the performance of ventilation systems



(a) (b)

Figure 3–Close-up view of test chamber walkway and pit area from (a) below the flooring, and (b) from above with the modular flooring removed for clarity.

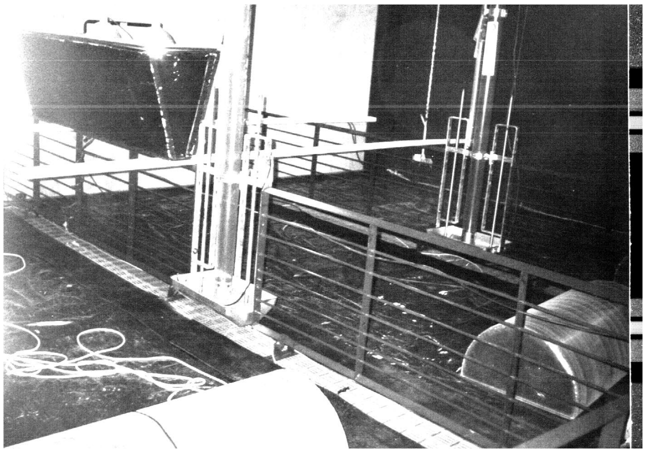


Figure 4–Interior view of test chamber showing one side consisting of three 8 ft × 20 ft pens. View shows gating, feeders, pig heat simulators, and modular flooring. Note: Only about 5% of modular flooring is showing in this picture. The remainder has been blocked off for conducting pit-ventilation studies.

and their auxiliary components. To simulate the influences of pigs, sensible heat production is added to the test chamber with twelve 660 W (2,253 Btu/h) cone resistance heaters. Two heaters are placed within each pen (fig. 2) under an aluminum dome perforated with small holes (fig. 5). Currently, the heaters can simulate sensible heat production from twenty-two, 100 lb (45.5 kg) pigs per pen.

Data Acquisition Capabilities

All data acquisition and control (DAC) requirements are provided with three independent yet compatible DAC systems (Model CR-10, Campbell Scientific, Inc, Logan, Utah). A layout of each of the three DAC systems is given in figure 6. The primary DAC system outlined in figure 6a is used to assess general operation variables of the test chamber. Air speed and temperature in each of the six pens, and auxiliary temperature throughout the test chamber are monitored. In addition, relative humidity of air entering the test chamber and at one central location within the test chamber, along with all monitored static pressures are collected with this primary DAC system.

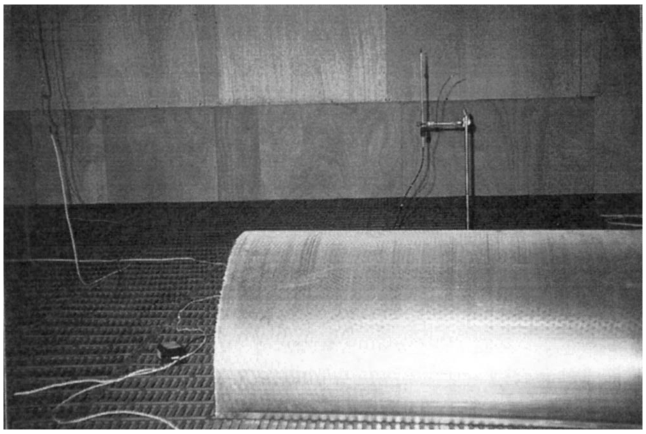


Figure 5–Animal occupied zone air speed and temperature sensors situated above perforated aluminum dome used for simulating sensible heat production from housed pigs.

A secondary DAC system is completely dedicated to provide additional airspeed and temperature sensing for 48 independent locations as required by a particular test (fig. 6b). A third DAC system is used primarily for controlling an automated positioning system for quantifying air jet characteristics from inlets (fig. 6c).

Under normal testing protocol, all monitored parameters are collected every 15 s. The hourly averages are computed and stored for later retrieval and analysis. Maximum air speed values over a 1-h period are also collected. When testing the response characteristics of a control system, all values are collected every 5 s and 1-min averages are computed and stored for later retrieval and analysis.

Sensing Techniques

For the primary DAC system, omni-directional airspeed sensors (Model 8470; TSI, Inc, St Paul, Minnesota) measure the air speed magnitude in selected regions of the test chamber. There is one sensor per pen as shown in figure 2. The air speed sensors are positioned 30 in. (76 cm) above the slats (fig. 5) in order to measure the airspeed *entering* the animal-occupied zone (AOZ). Thermocouples (T-type) are placed at the same location as the airspeed sensors. Additional sensors are located within the test chamber at the same location as the controller sensors in order to verify controller set-point accuracy. The temperature 6 in. (15 cm) from the ceiling, 6 in. from the slats, and in the attic plenum are also monitored. Eleven thermocouples in total are currently monitored by the primary DAC system.

The primary DAC system also retrieves relative humidity levels of the air entering the attic supply plenum and at one central location in the test chamber with capacitive-plate sensors (Model HMP356; Varsala, Inc.). These sensors have an accuracy of ±2% and a repeatability of ±1%.

The primary DAC system also retrieves all static pressure measurements. Micromanometers (Model 1430, Dwyer, Inc.) provide a manual feedback on static pressure and strain-gage based pressure transducers (Model 267; Setra Systems, Inc, Boxborough, Massachusetts) provide analog outputs for easy data retrieval and real-time analysis. Using both methods provides a check-and-balance system for static pressure measurement. Static pressures are measured across the test chamber, across the test room and the attic, and across the test room and the pit area of the test chamber. Barometric pressure measurement is made with a transducer-based sensor (Model 276; Setra Systems, Inc, Boxborough, Massachusetts) and is also collected with the primary DAC system.

The second DAC system is used exclusively for up to 48 air speed and temperature sensing pairs within the test chamber, with flexibility to place any of the sensor pairs at any location within the test chamber. These sensors were developed and calibrated in-house using the technique described in Zhang et al. (1996). The primary use of this system is to discretize air jet profiles from inlet systems and for multiple simultaneous airspeed and temperature measurements within the AOZ for further development and refinement of the proposed ventilation performance standard (Proposed ASAE Standard X567).

The third DAC system was incorporated to control an automated sensor positioning system developed previously

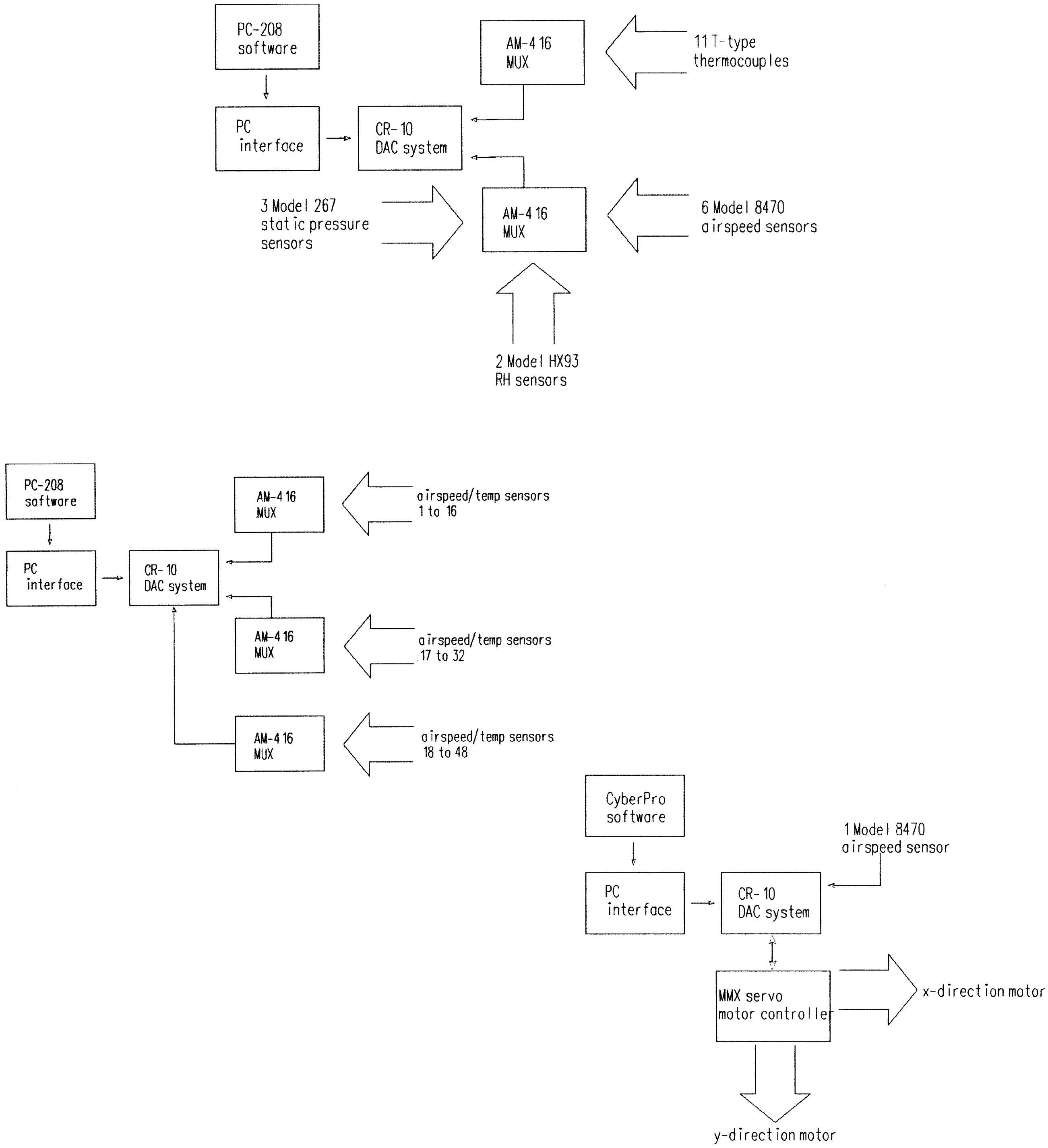


Figure 6–(a) Primary data acquisition system for system monitoring, (b) data acquisition system for 48-point air speed and temperature sensing, and (c) data acquisition and control system for automated sensor positioning.

(Dhawan, 1993) and refined for use in the current test chamber. The automated positioning and associated DAC system was developed specifically to evaluate air jet characteristics without entering the test chamber during testing. All data collection and control is accomplished outside the test chamber. For this system, one air speed (Model 8470, TSI, Inc., St Paul, Minnesota) and one temperature (T-type thermocouple) are sensed.

Specific Ventilation System Features Assessed

The focus of the ADL was to have the ability to assess all major operating characteristics of a field-operating livestock ventilation system. System energy efficiency, inlet and room characteristic graphs (Albright, 1990), air jet profiling, air speed and temperature uniformity, and controller performance are some of the major parameters assessed. Procedures for assessing these important ventilation features are described below.

System Energy Efficiency

The electrical energy consumption of a ventilation system being tested is monitored with manually read Watt-hour meters and supplemented with a digital programmable wattmeter (Model A1R-AL; ABB Power and T&D Company, Inc., Raleigh, North Carolina). Electrical energy input is monitored at the power entrance of all controllers used for a given ventilation system. Fan characteristics such as supply voltage and fan RPM (Ametek Model 1736 tachometer; Mansfield and Green Division) are measured throughout a given testing period. The system energy efficiency is recorded as the system CFM per watt, where the system CFM is defined as the total amount of *supply air* that is ventilated through the test chamber.

System Airflow Capacity

One of the key features assessed with any tested ventilation system is the airflow delivery rate by the fans and through the inlets as a function of the static pressures developed with the fans and across the inlets, respectively. The test chamber measures the volume of air flowing into the attic, through the animal occupied zone, and out the exhaust fans of the chamber.

Airflow into the test chamber is delivered to the attic plenum using calibrated square openings (calibrated at BESS Laboratories, Dept. of Agricultural Engineering, University of Illinois). The calibrated attic openings are positioned along one gable end of the test chamber as shown in figure 7. A total of nine openings were installed varying in size from 8 in. (20.3 cm) to 24 in. (61 cm) square. Three 8 in., two 16 in., and four 24 in. inlets provide a variety of combinations to achieve the correct balance of attic open area and static pressure drop across the attic inlets required for accurate measurement. A static pressure of 0.002 to 0.04 in. water gage (0.5 to 10 pascals) can be achieved for a desired airflow delivery of 60 to 11,200 ft^3/min (0.03 to 5.3 m^3/s).

Each inlet was calibrated independently. The three 8 in. inlets, which are located in close proximity to each other, were tested independently, two at a time, and three at a time to determine the effects, if any, of air stream interference. Each calibration test was conducted three times. The resulting regression line is the result of all data points obtained. Figure 8 shows the results of the calibration process.

Figure 7–Calibrated attic intake openings positioned on one gable end of the test chamber.

To assess leakage into the attic plenum and into the test room, a standard blower door test procedure provided air leakage data with the results presented in figure 9. The equation describing infiltration into the attic was $V_{attic} = 3533.5(\Delta P_{attic})^{0.582}$ and the equation describing infiltration into the room was $V_{room} = 939.4(\Delta P_{room})^{0.541}$. The leakage into the attic is added to the airflow through the calibrated attic inlets to quantify airflow through the ceiling inlet system. The leakage into the room is added to the airflow through the ceiling inlet system to quantify airflow through the fan system.

A QuickBasic® program allows inputs for attic, inlet, and room static pressures, the number of attic inlets in use, and the ambient temperature, barometric pressure, and relative humidity. The program then calculates and displays the following data:

- Actual and standard volume of air flowing through the attic inlets.
- Actual and standard infiltration.
- Actual and standard total airflow through the chamber.
- Actual and standard fresh-air exchanges per hour (ACH).
- CFM per square foot of open attic inlet area.
- Actual and standard uncertainty associated with all measurements.

Actual airflow data is the true magnitude of airflow as measured by the system. Standard airflow data is the airflow corrected to standard conditions of 1 atmosphere and 68°F (20°C).

Air Jet Profiling

The air jet profile from air inlets is found using the automated positioning system described previously (fig. 10). This system is able to determine a cross-section air speed profile of the inlet air as it enters the room through the inlet. A sampling plane with a horizontal distance of 5.5 ft. (1.68 m) and a vertical distance of 48.5 in. (1.23 m) from the exit of the inlet is divided into 288 points. The system is allowed to equilibrate for 1 min after moving to each position. Air speed and temperature data are collected for 3 min at a sampling rate of 8 samples/s.

The automated positioning system is controlled *via* an MMX stepper motor controller and CyperPro software (Mountain View, California). The resulting air jet profile is graphed in a three-dimensional surface graph using commercially available software.

Testing Procedure

The test chamber has been used primarily for evaluating the performance of commercially available livestock ventilation systems. Companies involved with this research were requested to design a ventilation system for the test chamber and a series of measurements were conducted to compare performance characteristics among manufactured systems. In addition, several other research projects related to heater control (Van Utrecht et al., 1999) and pit-ventilation effectiveness (Hoff et al., 1998) have been

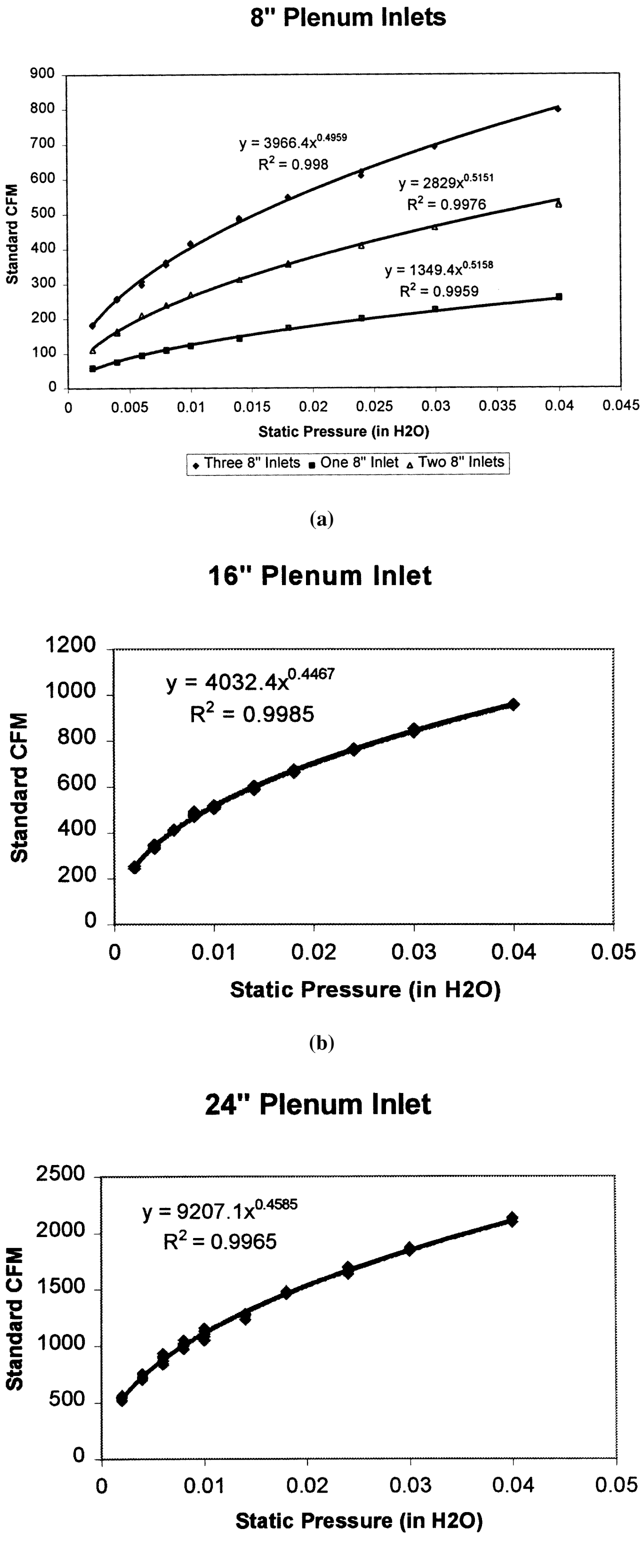


Figure 8–Calibration curves for (a) 8-in., (b) 16-in., and (c) 24-in. square attic intake openings.

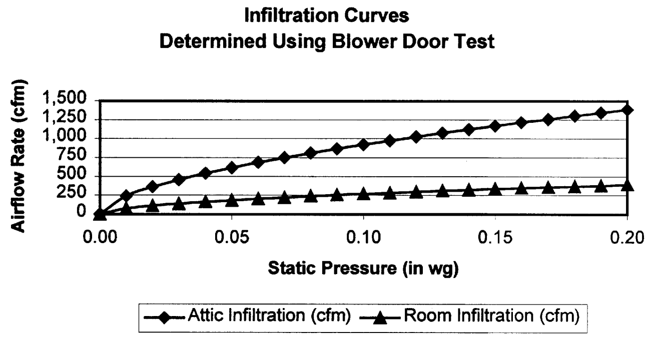


Figure 9–Attic and room infiltration curves derived from standard blower door test. Regression equations for infiltration (cfm) as a function of static pressure difference (in wg) across the attic plenum and room, respectively, were V^{attic} = 3533.5 (in wg)$^{0.582}$ and V^{room} = 939.4 (in wg)$^{0.541}$. Please note: The attic plenum is not allowed to operate above 0.02 in wg.

studied with this facility. The ADL is well suited for studying a wide variety of ventilation-related topics. The following description is the general procedure used for evaluating and comparing ventilation systems supplied by participating manufacturers as part of a past research project (Iowa Energy Center Project IEC 96-01, Iowa State University).

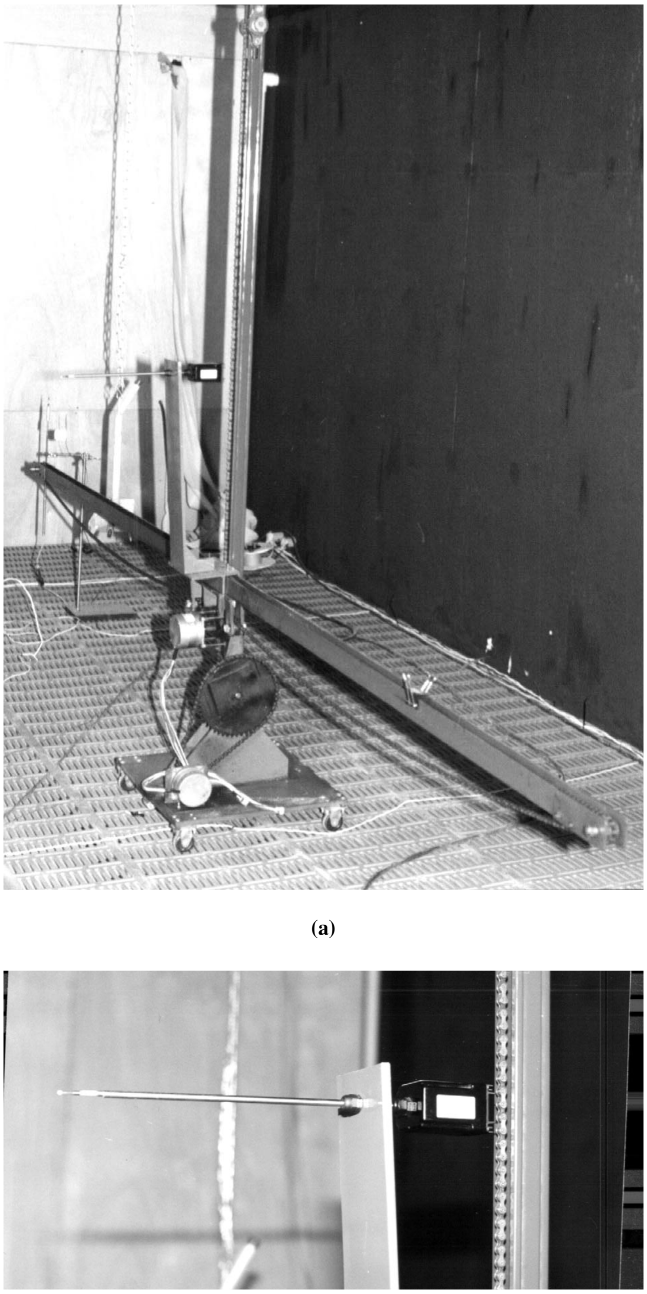
Equipment sent by each company is installed per installation guidelines supplied and each participating company is required to inspect all installed components before testing starts (fig. 11). Once a company feels that their system is ready for testing, a variety of tests are conducted to provide the manufacturer information related to energy and air distribution efficiency. Systems are tested at several ventilation rates, depending on the system provided by the manufacturer, and tests are conducted on the controller supplied as well. All components tested including any inlets, fans, controllers or auxiliary components such as stir fans are supplied by the company.

The first step when testing a ventilation system is to determine the number of calibrated attic intake openings to activate. The requirement for testing is to operate the ventilation system as if it were field installed. Therefore, the attic intake opening is sized so that no more than 450 CFM/ft^2 of opening exists (2.29 m^3/s-m^2). This level is consistent with current design recommendations (MWPS, 1995). A computer program written in QuickBasic® aids in the selection of the calibrated attic openings required. Airtight closures are provided for all attic inlets not required for a given test.

The static pressure across the calibrated attic openings, across the ceiling inlet system, and across the room (i.e., fans) is measured after a desired ventilation "point" is established. Simultaneously, the beginning watt-hour level, fan RPM, and controller voltage supply level are recorded.

Each ventilation "point" is allowed to operate at steady-state conditions for 24 h. The controller supply voltage and fan rpm levels are recorded approximately midway through the run and again at the end of the test, along with the ending watt-hour level. Depending on the ventilation system supplied, a series of 24-h ventilation "points" are investigated in this manner. In general, at least ten points have been studied which allows for enough data to characterize ventilation system performance using characteristic inlet and fan graphs.

Specific tests are conducted on the supplied control system during a simulated cold-weather mode of operation. Currently, the temperature of the air entering the test chamber cannot be lower than ambient conditions.

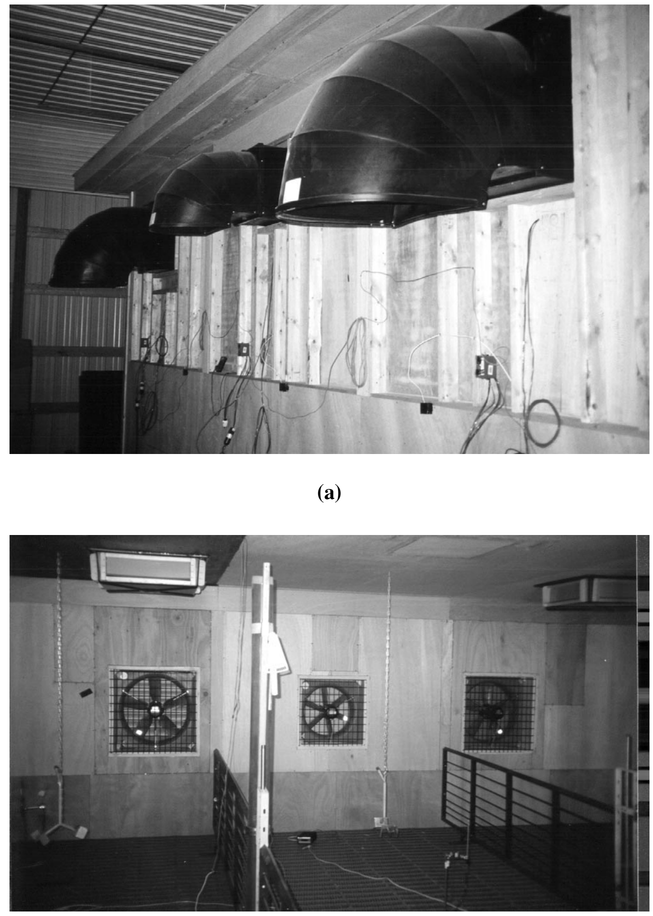


(a)

(b)

Figure 10–Automated sensor positioning system showing (a) system in place, and (b) air speed sensor.

Therefore, the ADL's supplemental heating system and the sidewall block-outs and overhead door of the ADL (fig. 1) are opened to control the air temperature surrounding and entering the test chamber. Two basic tests are conducted in this configuration, one where the set-point of the test chamber is set at a value of 20°F above ambient and one with a set-point of 40°F above ambient conditions. For example, if the temperature surrounding the test chamber is 60°F, the set-points tested would be 80°F and 100°F. The pig heat simulators are activated for this phase of the testing. After steady-state conditions are reached, variables are monitored for approximately 5 h.



(a)

(b)

Figure 11–(a) Exterior, and (b) interior views of the test chamber with a ventilation system ready for testing.

After all ventilation points and controller tests are completed, a series of performance results are calculated and a report is made for each manufacturer. The following section briefly describes the information summarized from this testing procedure.

PERFORMANCE SUMMARY

Table 1 and figures 12 to 15 provide a sample of test results summarized for each tested ventilation system. A complete summary and report of the testing results is provided to each participating company. Recommendations are not included in the report.

Table 1 provides in one table many of the results of testing. The first column indicates each ventilation "point" tested. For the example given, the ventilation system utilized three fans, labeled as fan 1, 2 or 3. Each point represents a ventilation rate using combinations of these three fans, and allowed to operate for 24 h. For the example given in table 1, ten 24-h tests were conducted. For each test point, the status of the fans is specified. For example, for test point 4, fans 1 and 2 were operated at full speed and fan 3 was not running. All fan variable speed settings are controlled by a company supplied controller.

For each test point, the operating fans are monitored at three specific periods over the 24-h test period. The fan

Table 1. Summary of test points

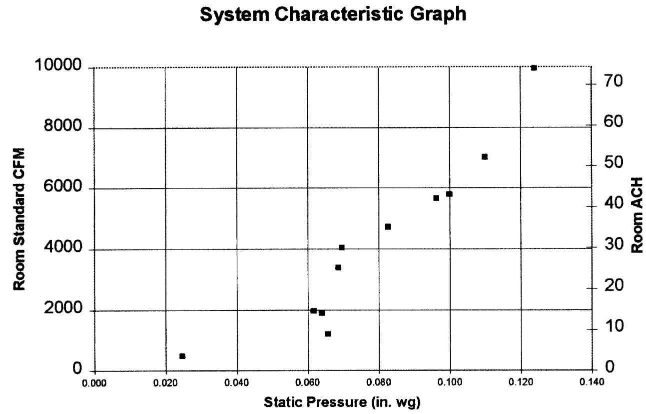
Point	Fan Status	RPM	VAC	Watts	CFM/ Watt	Inlet SP	Inlet CFM	Room SP	Room CFM
1	1 Full speed	1085							
	2 Full speed	1672	245.2	1015	9.9	0.106	8200	0.124	10000
	3 Full speed	1074							
2	1 Full speed	1086							
	2 Off		244.8	910	7.7	0.095	6700	0.110	7000
	3 Full speed	1073							
3	1 Full speed	1086							
	2 Off		245.2	405	9.9	0.061	3500	0.070	4000
	3 Off								
4	1 Full speed	1080							
	2 Full speed	1674	244.6	588	9.9	0.084	5500	0.096	5800
	3 Off								
5	1 Off								
	2 Full speed	1674	245.3	280	7.1	0.054	1700	0.062	2000
	3 Off								
6	1 50%	950							
	2 Off		244.9	734	8.0	0.088	5500	0.100	5900
	3 50%	887							
7	1 Off								
	2 Off		245.8	377	9.0	0.057	3100	0.069	3400
	3 50%	906							
8	1 Off								
	2 50%	1518	245.6	174	10.4	0.053	1600	0.064	1800
	3 Off								
9	1 Off								
	2 35%	864	245.8	62	8.1	0.014	300	0.025	500
	3 Off								
10	1 Off								
	2 43%	1308	246.0	159	7.5	0.053	1000	0.066	1200
	3 Off								

rpm and controller supply voltage levels are recorded with the average given as shown in table 1. Additionally, at three specific periods over the 24-h test period, static pressure across the test chamber, inlets, and attic plenum are recorded. For each of these three measurements, the inlet and fan CFM levels are recorded. The average is reported as shown in table 1. At the end of the 24-h test period, the total energy consumption is recorded and the *system* CFM/watt is recorded.

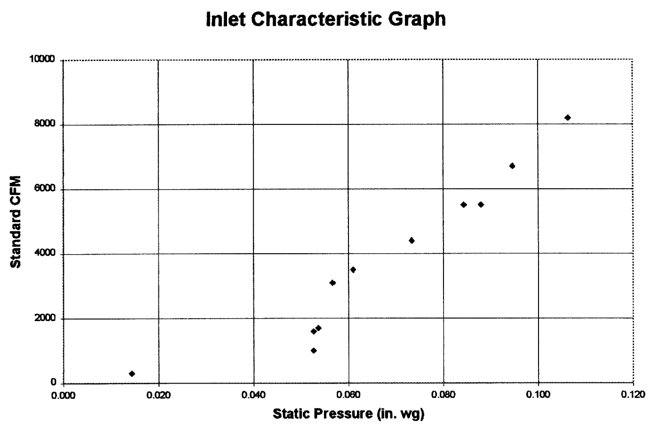
To help visualize the results given in table 1, the System and Inlet Characteristic Graphs are given as shown in figure 12. In addition, the system energy efficiency, as a function of the fresh-air ventilation rate, is given as shown in figure 13.

Additional information collected during the testing process is summarized as shown in figures 14 and 15. Figure 14 highlights a typical result from air jet profiling from one randomly selected inlet supplied by the manufacturer. This information is supplied to help manufacturers verify whether the inlet and fan system resulted in operating static pressures across the inlet system that resulted in proper air jet profiles including the exit airspeed from the inlet.

Figure 15 highlights the result from testing the controller supplied. The basic test conducted on each controller supplied was the ability to maintain the AOZ temperature at the specified set-point temperature. With each controller supplied, the AOZ temperature is compared with the desired set-point temperature. Two specific test cases are conducted. The first test involves having the ventilation system maintain the set-point temperature 20°F above ambient conditions. During this mode of operation, supplemental heat typically is not needed and a representative ventilation system response is shown in



(a)



(b)

Figure 12–Summary of airflow (a) through the test chamber as a function of the room operating static pressure, and (b) through ceiling inlets at inlet operating static pressures.

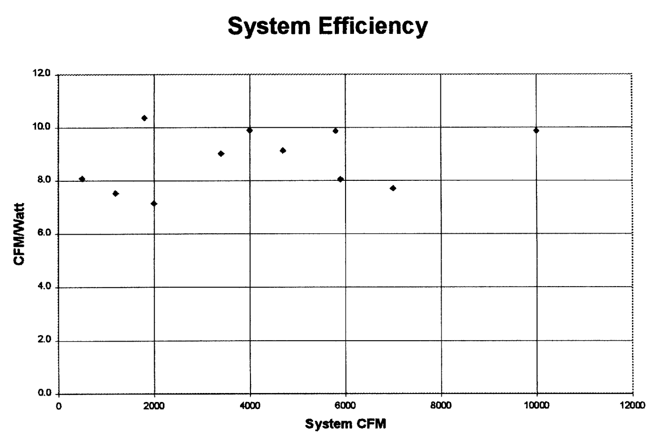


Figure 13–System energy efficiency at each ventilation point tested.

figure 15a. For this example, the six AOZ temperatures are plotted in time for the six zones shown in figure 2. At 110 min and beyond, the ventilation system is operating at steady-state conditions and it is during this period that results are summarized for the manufacturer. For the example given, excellent control is shown.

To test controller activation of supplemental heaters, in conjunction with a ventilation system operating at

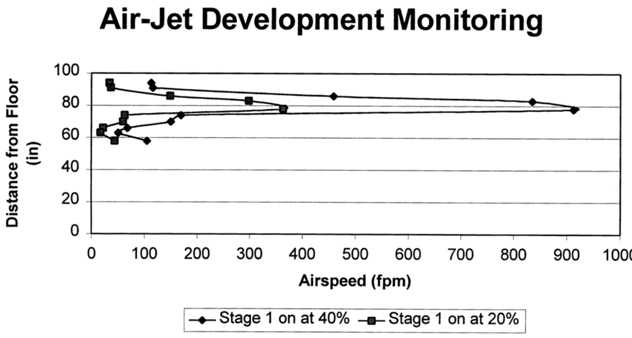
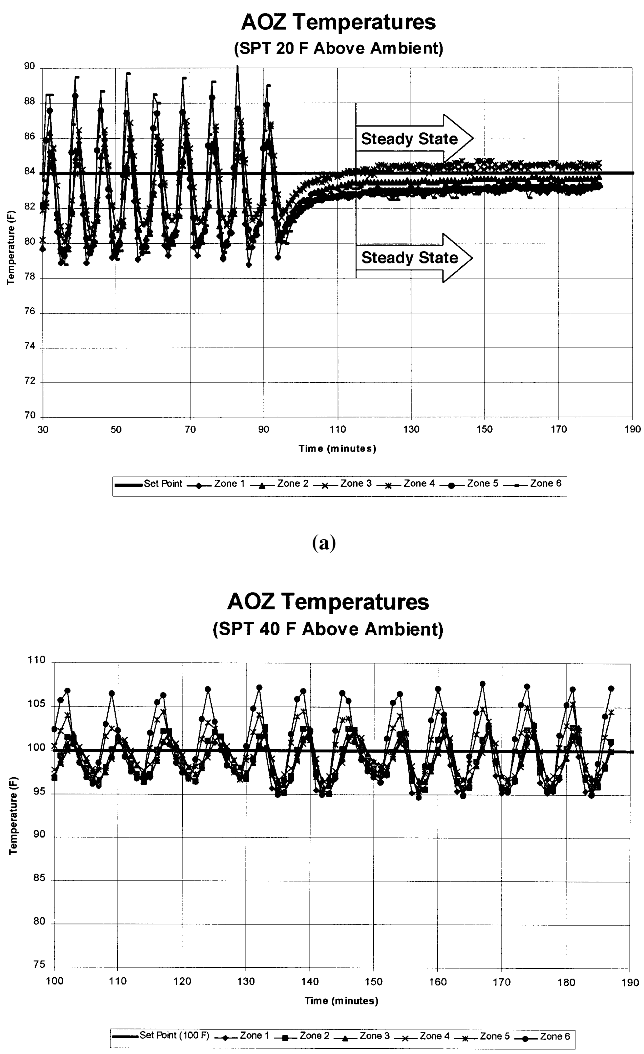


Figure 14–Velocity profiling example for a randomly selected inlet. Example shows the air jet development at the exit point of the inlet, and for two variations in airflow rate.



(a)

(b)

Figure 15–Controller response characteristics when maintaining room temperature (a) 20°F above ambient, and (b) 40°F above ambient.

minimum ventilation, the controller was then instructed to maintain the inside temperature 40°F above ambient conditions. A typical result from this test is given in figure 15b for the six AOZ zones specified in figure 2. The on/off activation of the supplemental heater is quite apparent, and was a typical response from all ventilation systems tested. Temperature swings reaching 12 to 14°F every 10 min were not uncommon. Clearly, the on/off nature of heater control drastically effects the ability to maintain the AOZ temperature at the desired set-point. It should be noted that the temperature sensors used for monitoring were far more responsive than the typical thermally massive sensors used by the controllers. Therefore, the controller never sensed these large temperature swings, but in reality they were always present as indicated in figure 15b. Current work is underway to develop a heating and control system to eliminate these excessive temperature swings (Van Utrecht et al., 1999).

Summary

A general purpose laboratory, called the Air Dispersion Laboratory (ADL), has been developed to test many operating characteristics of commercially available livestock ventilation systems, and for research on new innovations for the industry. The ADL is devoted to ventilation system testing, where fans, inlets, and controllers are allowed to work together as if field installed. Many useful results related to airflow versus operating static pressure, air jet development, temperature and airspeed uniformity, and system energy efficiency can be easily investigated in a controlled clean-room facility.

Research and proof-of-concept studies can and have been investigated related to other livestock control issues that currently exist today, especially as it relates to supplemental heater control and pit-ventilation issues (Hoff et al., 1998; Van Utrecht et al., 1999).

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